

Final Report

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The results of the research conducted under this grant are presented in detail in three Master theses by Heinrich<sup>1</sup>, Balow<sup>2</sup>, and Broeren<sup>3</sup>. Additional analysis of the experimental data can be found in two AIAA Journal articles<sup>4,5</sup> and two conference papers<sup>6,7</sup>.

The objective of Heinrich's study<sup>1</sup> was to document the low-frequency flow oscillation on the LRN-1007 airfoil which had been previously observed at low Reynolds number, to determine its origin, and explore the phenomenon at higher Reynolds number. Heinrich performed detailed flow visualization on the LRN airfoil using surface fluorescent oil and laser-sheet off-body visualization. A large leading-edge separation bubble and trailing-edge separation was identified on the airfoil just prior to the onset of the unsteady stall flow oscillation. From the laser-sheet data, the unsteady flow appeared as a massive boundary-layer separation followed by flow reattachment. Hot-wire data were taken in the wake to identify the presence of the flow oscillation and the dominant frequency. The oscillation was found in the flow from a Reynolds number of  $0.3$  to  $1.3 \times 10^6$  (the entire range of Re studied). The Strouhal number based on airfoil projected height was nominally  $0.02$  and increased slightly with increasing Reynolds number and significantly with increasing airfoil angle of attack. Preliminary results from Heinrich's study were published by Bragg, Heinrich and Khodadoust<sup>4</sup> and a more complete summary including a detailed review of the potentially related shear-layer-flapping phenomena was reported by Bragg, Heinrich and Zaman<sup>6</sup>.

Balow<sup>2</sup> focused his research on the leading-edge separation bubble which was hypothesized to be the origin of the low-frequency oscillation. Initially, experimental measurements in the bubble at the onset of the low-frequency oscillation were attempted to study the characteristics of the bubble and explore possible relationships to the shear-layer-flapping phenomena. Unfortunately, the bubble proved to be extremely sensitive to the probe interference and it drastically reduced the size of the bubble. These detailed measurements were then abandoned by Balow. However, this led to a series of tests where the leading-edge bubble and trailing-edge separation were altered and the effect on the flow-oscillation studied. Balow found that by tripping the airfoil boundary-layer with "zig-zag" tape ahead of bubble separation, the bubble was effectively eliminated and the oscillation suppressed. Wake survey drag measurements showed a dramatic reduction in airfoil drag when the bubble and oscillation were eliminated. Using the "zig-zag" tape,

the trailing-edge separation was moved downstream approximately 5% chord. This was found to reduce the amplitude of the oscillation, particularly in the onset stage at low angle of attack (around  $14^\circ$ ). Through detailed analysis of the wake behind the airfoil during the unsteady flow oscillation, Balow provided a better understanding of the wake flowfield. A brief summary and analysis of these data can be found in the journal article by Bragg, Heinrich and Balow<sup>4</sup>.

Broeren<sup>3</sup> studied the oscillating flowfield in detail at  $Re = 3 \times 10^5$  and an angle of attack of  $15^\circ$  using laser Doppler velocimetry, LDV. Two-dimensional LDV data were acquired at 687 grid points above the model upper surface while hot-wire data were taken simultaneously in the wake. Using the hot-wire signal, the LDV data were phase averaged into 24 bins to represent a single ensemble average of one oscillation cycle. The velocity data showed a flowfield oscillation that could be divided into three flow regimes. In the first regime, the flow over the airfoil was completely separated initially, the flowfield reattached from the leading edge and the reattachment point moved downstream with increasing time or phase. Broeren referred to this as the reattachment regime. The bubble development regime followed, where a leading-edge separation bubble formed at the leading edge and grew with increasing time. During the initial part of this regime the trailing-edge separation continued to move downstream. However, during the last 30 degrees of phase the trailing-edge separation moved rapidly forward and appeared to merge with the leading-edge bubble. The third regime was referred to as the separation regime. During this part of the oscillation, the flow was separated from the airfoil leading edge and did not reattach to the airfoil surface. The reverse flow was seen to grow in vertical extent up from the model surface as the phase increased. Next, reattachment began again at the leading edge signaling the start of the reattachment regime, and so the cycle continued. From Broeren's work, the details of the unsteady flowfield over the airfoil were seen for the first time. Additional analysis of this work can be found in Broeren and Bragg<sup>7</sup>.

From this research a great deal has been learned about the low-frequency flow oscillation which naturally occurs on the LRN-1007 airfoil near stall. The oscillation was seen to persist at higher Reynolds number, the dependence of the Strouhal number on angle of attack and Reynolds number were discovered, the critical role played by the laminar bubble was shown and the entire upper surface flowfield during a flow oscillation cycle was measured and analyzed. What still eludes understanding is the scaling of the flow oscillation and why certain airfoils, such as the LRN, have a very strong low-frequency mode and other airfoils exhibit no organized low-frequency oscillation at all. These are the subject of the continuing research into the low-frequency flow oscillation currently underway at the University of Illinois.

## REFERENCES

- <sup>1</sup> Heinrich, D.C., "An Experimental Investigation of a Low-Frequency Flow Oscillation Over a Low-Reynolds Number Airfoil Near Stall," M.S. Thesis, University of Illinois at Urbana-Champaign, IL, 1994.
- <sup>2</sup> Balow, F.A., "Effect of an Unsteady Laminar Separation Bubble on the Flowfield Over an Airfoil Near Stall," M.S. Thesis, University of Illinois at Urbana-Champaign, IL, 1994.
- <sup>3</sup> Broeren, A.P., "Phase-Averaged Flowfield Measurements About an Airfoil in Unsteady Stall," M.S. Thesis, University of Illinois at Urbana-Champaign, IL, 1996.
- <sup>4</sup> Bragg, M.B., Heinrich, D.C., and Khodadoust, A., "Low-Frequency Flow Oscillation Over Airfoils Near Stall," *AIAA Journal*, Vol. 31, No. 7, July 1993, pp. 1341-1343.
- <sup>5</sup> Bragg, M.B., Heinrich, D.C., Balow, F.A., and Zaman, K.B.M.Q., "Flow Oscillation Over an Airfoil Near Stall," *AIAA Journal*, Vol. 34, No. 1, Jan. 1996, pp. 199-201.
- <sup>6</sup> Bragg, M.B., Heinrich, D.C., and Zaman, K.B.M.Q., "Flow Oscillation Over Airfoils Near Stall," ICAS Paper 94-4.5.2, 19th Congress of the International Council of the Aeronautical Sciences Conference Proceedings, Vol. 2, Sept. 1994, pp. 1639-1648.
- <sup>7</sup> Broeren, A.P. and Bragg, M.B., "Phase-Averaged LDV Flowfield Measurements About an Airfoil in Unsteady Stall," AIAA Paper 96-2494-CP, Proceeding of the 14th AIAA Applied Aerodynamics Meeting, New Orleans, June 17-20, 1996, pp. 921 - 931.